New optical polarization measurements of the Crab pulsar

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Abstract. The Crab nebula and its pulsar have been observed for about 3 hours with the high-speed photo-polarimeter OPTIMA in January 2002 at the Calar Alto 3.5 m telescope. The Crab pulsar intensity and polarization are determined at all phases of rotation with higher statistical accuracy than ever. Therefore, we were able to separate the so-called 'off-pulse' phase emission (with an intensity of about 1.2% compared to the main peak, assumed to be present at all phases) from the pulsed emission and show the 'net' polarization of the pulsed structures. Recent theoretical results indicate that the measured optical polarization of the Crab pulsar is similar to expectations from a two-pole caustic emission model or a striped pulsar wind model.

INSTRUMENT AND OBSERVATIONS

OPTIMA (Optical Pulsar TIMing Analyzer) has been built and developed at Max Planck Institute for Extraterrestrial Physics in Garching. The instrumental sensitivity (white light) extends from about 450 nm to 950 nm and the used polaroid filter modulates the incoming radiation effectively for wavelengths shorter than 850 nm. Astronomical targets are imaged onto a hexagonal bundle of optical fibers which are coupled to single avalanche photodiode photon counters. The spacing and size of the fibers corresponds to about 2 arcsec. GPS based time tagging of single photons, together with the instantaneous determination of the orientation of a rotating polaroid filter (by using the Hall probe), allows to measure the phase dependent linear polarization state of the pulsar and the surrounding nebula simultaneously. Detailed description of the instrument can be found at the MPE OPTIMA web page [1], as well as in [1], [2], and [3]. The observations were performed in January 2002 by using the OPTIMA instrument attached to the 3.5 m telescope at the Calar Alto Observatory.

POLARIZATION OF TOTAL EMISSION OF THE CRAB PULSAR

The Crab pulsar is detected at all phases of rotation (Fig. 1), i.e. also in the so-called 'off-pulse' phase with an intensity of about 1.2% compared to the intensity of the main peak.

[1] `http://www.mpe.mpg.de/gamma/instruments/optima/www/optima.html`

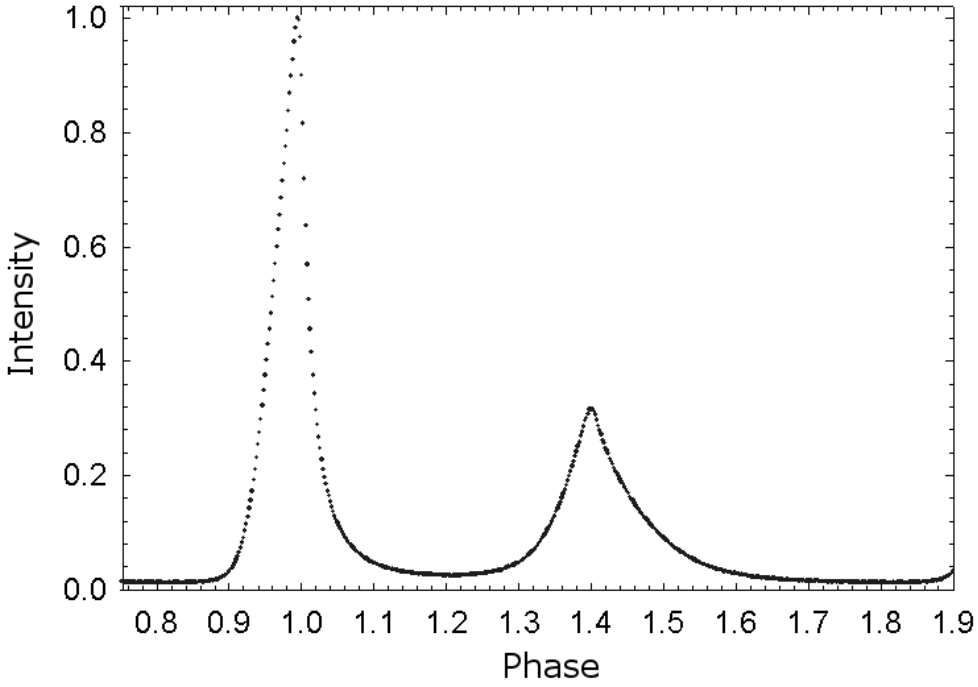

FIGURE 1. Normalized light curve of the Crab pulsar obtained by OPTIMA at Calar Alto Observatory in January 2002. The so-called 'off-pulse' phase emission within phase range 1.72-1.82 is on the level of 1.2% of the main peak intensity.

This confirms the result of [4]. From this measurement the polarization characteristics of the Crab pulsar shown in Fig. 2 were derived. The degree of polarization and the position angle (P.A.) of the E-vector are plotted with a resolution of 500 phase bins. Our result agrees generally well with the previous measurements ([5]), but shows details with much better definition and statistics. The variations of the P.A. observed for the Crab at optical wavelengths differ from those observed at radio wavelengths ([6], [7], [8]). There might be two reasons for it. Firstly, it can be caused by the restricted range of altitudes where the radio emission at any fixed frequency originates (contrary to the wide range of altitudes assumed in the high energy emission models, e.g. TPC=two pole caustic and OG=outer gap). Secondly, the P.A. may depend strongly on photon energy.

POLARIZATION OF THE PULSED COMPONENT ONLY

Constancy of the position angle within the phase range 1.7-1.9 (Fig. 2) may suggest that the optical emission from the Crab pulsar consists of two, pulsed and unpulsed, components: (i) one characterized by a highly variable P.A. and polarization degree, and (ii) a DC component with constant intensity on the level of 1.24% of the main pulse intensity, fixed P.A. (123°), and a degree of polarization on the level of 33%. Assumming that the continous component is present at all phase angles and has constant polarization

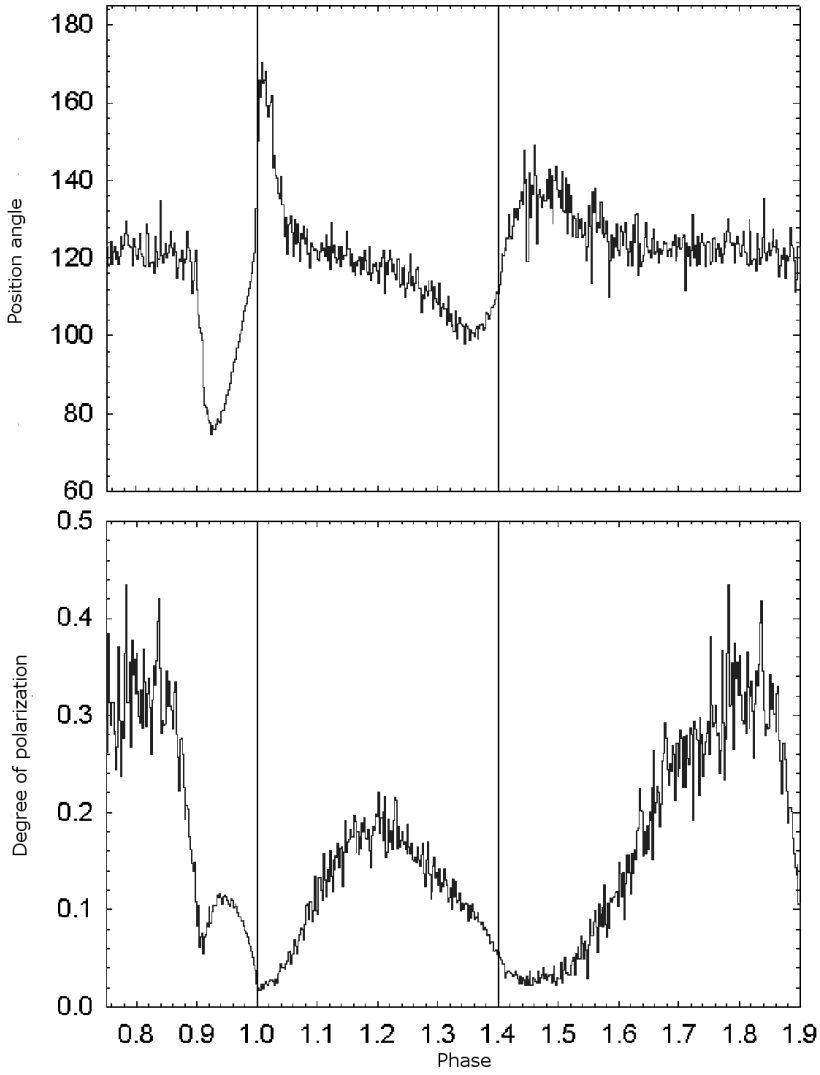

FIGURE 2. The position angle (E by N) and the degree of polarization of the E-vector on the sky for the Crab pulsar. This result are generally consistent with a previous measurement by [5] but shows details with much better definition and statistics. Please note that the degree of polarization has to be considered as preliminary. A correction for the wavelength dependent modulation depth of the polaroid filter used in this measurement has not yet been applied. We expect the degree of polarization in the corrected version to be slightly larger than shown here.

we obtained the polarization characteristics of the 'pulsed component' separately (Fig. 3) by subtracting the respective Stokes parameters I, Q, U from the linear polarization data. For comparison the light curves and polarization characteristics obtained within the framework of three high energy magnetospheric emission models of pulsars, the polar cap model, the two-pole caustic model, and the outer gap model are shown in Fig. 4. The two-pole caustic model ([10]) predicts fast swings of the postion angle and minima in the polarization degree, similar to what is observed. Polar cap model and outer gap model are not able to reproduce the observational polarization characteristics of the Crab

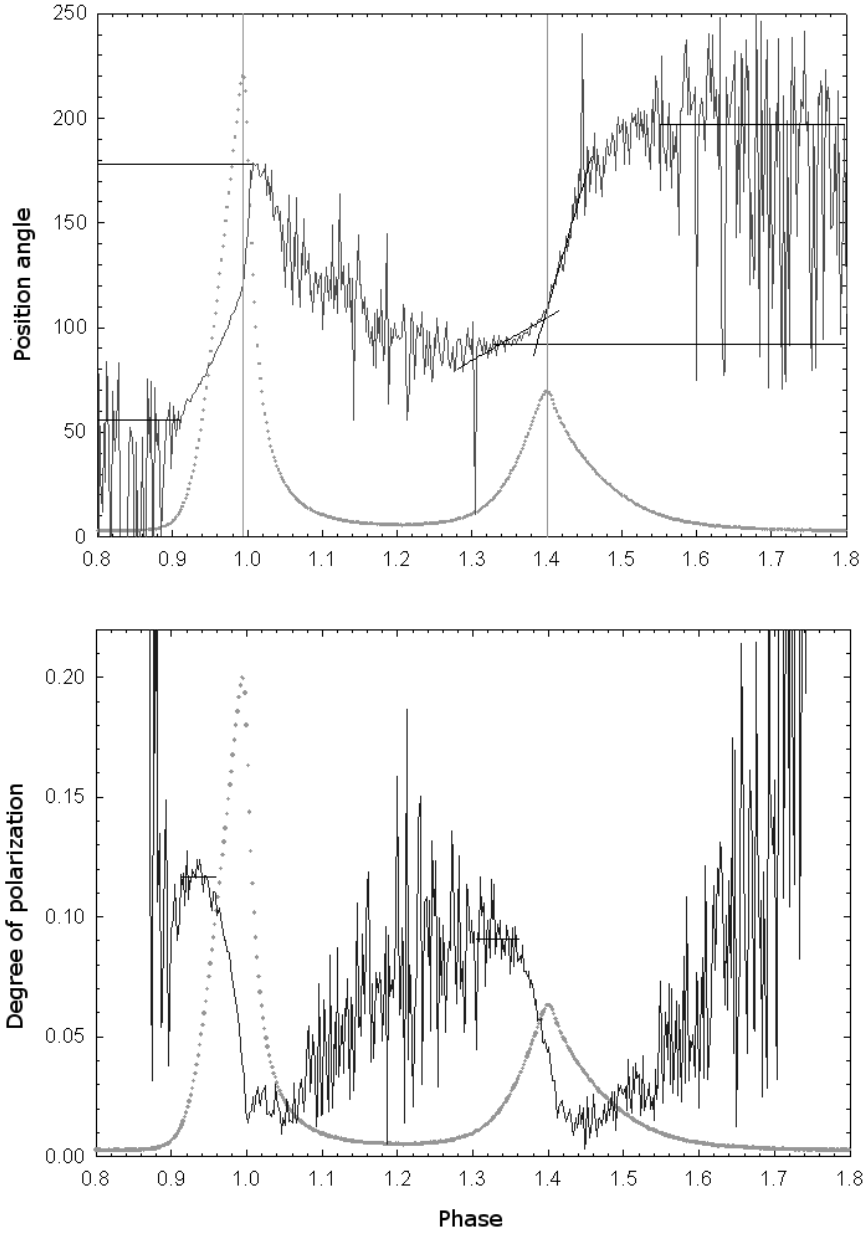

FIGURE 3. Polarization characteristics, P.A. and the degree of polarization, of the 'pulsed component' of the Crab pulsar. For clarity the light curve of the Crab pulsar is overplotted (grey dotted-line).

pulsar. Another model, placeing the origin of the pulsed optical emission from the Crab in a striped pulsar wind zone has recently been proposed by [11]. This model features also polarization characteristics that bear a certain resemblance to the observations.

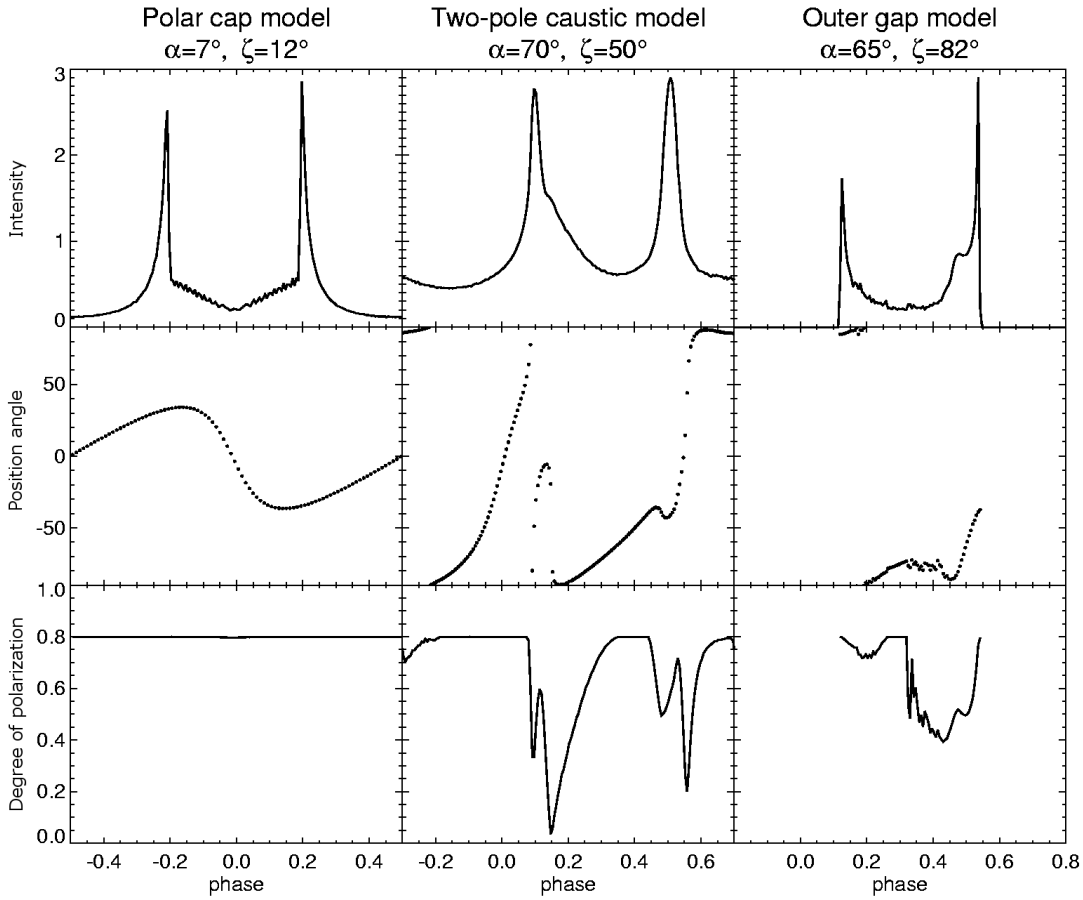

FIGURE 4. The optical light curve, the position angle and the degree of polarization calculated with the following models of high energy radiation from pulsars, from left to right: the polar cap model, the two-pole caustic model, and the outher gap model ([9]).

CONCLUSIONS

- The optical emission from the Crab pulsar is highly polarized, especially in the bridge and 'off-pulse' phase.
- The degree and angle of linear polarization show well defined structures:
  - at the peaks of the light curve the degree of polarization is minimal,
  - there is a well defined bump in polarization on the rising flank of the main pulse (possibly also for the inter pulse),
  - the polarization angle swings through a large angle in both peaks: after subtraction of an assumed constantly polarized continous emission (intensity on the level of 1-1.5% of the main pulse) the angles swing for 125° and 105° for the main pulse and inter pulse, respectively.
- The polarization signatures observed for the Crab show a high degree of similarity with theoretical estimates published by [12] in the framework of the two-pole

caustic model of magnetospheric emission or the characteristics derived in a striped pulsar wind model by [11].

ACKNOWLEDGMENTS

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